

Article

Investigation of the Substitutability of Rubber Compounds with Environmentally Friendly Materials

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Abstract: Rubber is one of the rare materials that can be used in many sectors and for multiple purposes. It can be used in a wide range of frameworks, from very simple coating materials to very complex spacecraft parts. Apart from natural rubber, compounds are also used for different purposes in rubber production. For a product with such a wide range of uses, the sustainability of its compounds is particularly important. The objective of this study is to investigate environmentally friendly and sustainable alternatives for rubber and some compounds, such as fillers and softeners. By doing this research with an academic method, the most suitable option is determined by taking the weights of the factors affecting this decision into consideration. As a result, the most suitable rubber, filler, and softener options are presented.

Keywords: rubber; rubber compounds; tire production; multi-criteria decision making; analytic hierarchy process



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1. Introduction

Rubber is a material that is obtained naturally from the milky sap of some plants or artificially from a combination of petroleum and alcohol. Rubber, an important engineering material, has a multipurpose and wide usage potential. Today, the use of the term “rubber” is no longer limited to the original natural rubber; instead, it applies to any material with properties similar to those of natural rubber, regardless of its chemical composition. The more modern term “elastomer” is used for synthetic materials with properties similar to rubber.

Rubber is a material that has a wide range of uses. It appears in many products we use in daily life, especially in the automotive sector [1]. Approximately 70% of rubber produced is used in the production of vehicle tires [2].

Natural rubber provides important properties, such as tear and fatigue cracking resistance expected from tires. Synthetic rubber polymers used in tire production are used in combination with natural rubber since they cannot provide the desired properties on their own. The physical and chemical properties of synthetic rubber compounds determine the performance of each component in the tire and the performance of the tire, such as

rolling resistance, abrasion, and traction. Synthetic rubbers also make the inner part of the tire more impermeable.

Rubber is produced in two ways: the first way is the production of natural rubber from the latex of the *Hevea brasiliensis* tree, grown especially in the Far East; and the second way is the production of synthetic rubbers from petroleum through various processes.

Natural rubber (NR) is produced commercially from the latex of the *Hevea brasiliensis* tree which is grown in the tropics of Southeast Asia, especially in Malaysia and Indonesia. The polymer chains of natural rubber are in the form of long, intertwined coils and are in constant motion at room temperature. The twisting and wrapping of natural rubber polymers are a result of the inhibition of the three-dimensional order formed by the methyl group and the hydrogen atom, which are on the same side with the carbon-carbon double bond [3].

Today, NR accounts for about 46% of the total rubber consumed worldwide [4]. NR is almost exclusively the only material used to date with zero tolerance in quality and performance behavior, such as in heavy-duty truck tires and aero tires. NR differs from its alternatives by displaying excellent crystallization properties. NR fully meets the tensile properties, flex-fatigue resistance, and cut resistance properties expected from the end products it is used in [5].

Parthenium argentatum (Guayule, GR) has been used extensively in industry, academic studies, and projects as an alternative to Hevea rubber, and it is expected to be used in the future. [6]. Russian dandelion (*Taraxacum kok-saghyz*) is a type of dandelion native to Kazakhstan of the former Soviet Union [7]. It is conceivable that the use of synthetic rubber in the tire carcass and tread compound of the Russian dandelion will make tires more sustainable.

Synthetic elastomer technology has reached its current status by projects carried out with the support of governments in both academia and industry. The basic building blocks of almost all synthetic elastomers are derived from petrochemicals (mostly fossil fuels). The beginning of the 20th century saw an increase in the use of synthetic elastomers, a new class of materials derived from fossil sources.

Rubber mixture is the process of selecting and mixing appropriate rubber and raw materials and compounds in order to obtain the desired properties from the finished product. The group of items selected according to the purpose and providing proportional integrity with each other is called a prescription or formula [8].

The proportions in rubber technology are based on the principle that rubber, which is the main raw material, is accepted as 100 units by weight. All materials used except rubber are prescribed as PHR (part per hundred rubber), the amount required for one hundred rubber. Table 1 shows the raw materials and quantities used in the recipe in order to obtain the desired properties from a rubber compound [9].

Table 1. Rubber recipe sample to be used in tire manufacturing.

Raw Materials	PHR
Rubber	100
Fillers	50
Softeners	10
Process aids	1–5
Activators	5
Accelerators	1–2
Vulcanizing agents	0–2
Anti-agings	1–2

The tire rubber compound should provide the best performance triangle of grip, rolling resistance, and wear resistance. For good grip, the coefficient of friction between the tire and the road should be as high as possible. At the same time, fuel consumption can be improved by reducing rolling resistance. Fillers have the highest impact on the

rolling resistance performance of the tire. As the last corner of the triangle, wear resistance is related to the durability of the tire and environmental considerations. In particular, the outer surface of the tire in contact with the road is expected to be resistant to abrasion. When one of these features is improved, it will have to be at the cost of others; therefore, the tire compound should be specially prepared according to the usage area of the rubber.

Very small particle size materials added to rubber paste as dry powder are called reinforcing or filling materials [10]. Fillers are used for purposes such as strengthening the rubber, improving its processability, and decreasing the price and color. Fillers can be in dry powder form and inorganic or organic [11].

In commercial applications of elastomers, fillers are generally used to provide the desired properties [12]. The main reason for this is to improve certain properties of the composition and reduce the cost [13]. Fillers can be classified in two different ways, according to their color and their effect. It is possible to divide these, according to their color, into black and white fillers and, according to their effect, into active fillers (reinforcer), semi-active fillers (partially reinforcing), and inactive fillers (without reinforcing effect) [10]. Black fillers are carbon blacks, and white fillers consist of fillers such as calcium carbonate, silica, clay, talc, zinc oxide. Silica has long been used in rubber processes to reinforce rubbers. Silica is used to increase the wet performance of the tire and to maintain its flexibility in cold weather. The silicas used in the rubber mixture have particle size distributions in the nanometer range. In addition, they are in an amorphous precipitated form as well-defined aggregates of almost monodispersed spheres. Silica is not a functional filler for rubber tires without a bonding agent. For this reason, coupling agents that can react with both the silica surface and the rubber molecule are often used. It is possible to use silica in rubber mixtures only by using sulfur silanes. The silanization method is also used with environmentally friendly natural fillers [14–17]. By using silanization, the rubber-filler interaction is improved and significantly improved reactions are achieved.

Carbon black is a semi-graphite amorphous carbon that increases the tensile strength, modulus, abrasion resistance, and tear strength of rubber when mixed with rubbers [18]. Almost all carbon blacks produced in the world are used in the rubber industry. Besides from the rubber industry, it is used as a dye, plastic, printing ink, and absorbent material. Methane gas obtained in petroleum and natural gas is obtained partially (in low and controlled oxygen environments) or as a result of thermal decomposition of heavy and light petroleum oils and aromatic hydrocarbons. Since it is a fossil-fuel-based material, it is a problematic additive material in terms of sustainability.

Carbon black is obtained from non-renewable resources through the processing of oil. Therefore, the carbon black industry produces carbon dioxide emissions that cause global warming. Due to the high dependence of carbon black on petroleum resources and increasing oil and carbon black prices, more effective measures have been taken to reduce global warming. This has led to studies exploring environmentally friendly carbon black alternatives.

In recent years, there has been an increase in the search for renewable and green materials to replace carbon black. Different natural alternatives and their properties have been compared with carbon black [19,20]. When looking at the literature, naturally sourced filler options, bamboo, pineapple, starch, and organoclay, stand out as more promising than others.

Softeners are used as process facilitators in the preparation of the mixture. Process facilitation occurs at different stages of rubber production. We can list the usage purposes of softeners as follows: (i) to reduce friction during mixing by wetting rubbers and fillers; (ii) to enable easier mixing by reducing the viscosity of the mixture during mixing; (iii) to provide a homogeneous mixture; and (iv) to reduce the risk of precooking by providing a low mixing temperature.

Softeners are generally divided into two classes: physical and chemical. Generally, their interactions with rubbers are taken into account when classifying. Chemical softeners involve the chemical softening of the rubber through peptization; the chemical substances

involved are called peptizers. Substances used as peptizers include phenylhydrazine salts, aromatic mercaptans, diphenyl sulfide, and alkyl aryl sulphonates [21].

Physical softeners significantly affect the mixture and the product. Even softeners can act as cheapeners. Physical softeners are divided into three classes: mineral oils, synthetic oils, and natural oils. Natural oils are divided into animal and vegetable oils. These oils are not commonly used today as developments in technology have made petroleum the main oil source. However, petroleum oils are not a sustainable option. For this reason, environmentally friendly natural oils should be preferred for use in rubber production. Examples of vegetable oils are palm oil, soybean oil, cottonseed oil, sunflower oil, and hazelnut oil.

Studies have been conducted on the replacement and application of vegetable oils as additives in polymer processing [22,23]. It was shown that epoxidized vegetable oils (EVO) can be used as processing aids for polymers [24,25]. Previous studies using palm, soybean, and sunflower oils as alternative emollients and activators showed the possibility of using certain vegetable oils as processing aids [23].

Sustainability has been defined by various international organizations such as the United Nations Climate Change Conference (Conference of the Parties), the European Climate Change Adaptation Conference, the World Climate Summit, government bodies, and scientific consortiums. It is stated that the most generally accepted definition of sustainability is “to meet the needs of the present generation without compromising the needs of future generations in order to meet their own needs” [24,26]. In recent years, a large number of academic articles and books on the progress in polymer science and technology and the importance and future of sustainability have been prepared [27].

Although it is an extremely important engineering material, no systematic decision-making method has been used for sustainable developments in the field of rubber science and technology. This study aimed to find sustainable alternatives to rubber and compounds used in tire production, the sector where rubber is used the most. This aim was transformed into decision problems in three stages, and the solution was reached by using multi-criteria decision-making methods. Firstly, natural rubber options are compared, and the most sustainable alternative is determined. Environmentally friendly alternatives that can be used instead of carbon black are evaluated, and then the most sustainable alternative among the oils used for softening purposes is determined. In addition, which criteria affect the results at each stage and the scale of the effect is determined. As a result, a roadmap for areas to work on academically and recommendations to make the sector more environmentally friendly are provided.

In the next section of the study, the analytical hierarchy process (AHP) method, which is one of the multi-criteria decision-making methods used to determine the most suitable option among the alternatives, is explained. In the application section, the determination of decision problems, creation of hierarchical structures, and analysis of these probes with the AHP method is shown. In the following section, the weight values of the alternatives and criteria obtained as a result of the solution of the problems are presented and short interpretations are made about these results. In the final section, the extent the study addresses the problem it deals with, its limitations, and how future studies can be directed are explained, followed by academic and sectoral advice.

2. Materials and Methods

AHP, linear programming, and fuzzy logic are more understandable and easier than other math tools. Moreover, AHP can divide decision problems into smaller problems and simultaneously enable qualitative and quantitative criteria to be compared. Thus, problem-related thinking processes are made simpler and more systematic. Due to these comparability and simplification advantages, the AHP method was used in accordance with the structure of the problem in this study.

AHP was developed by Thoman L. Saaty at the Wharton School of Business in the 1970s for solving multi-criteria decision-making problems. In this method, expert opinion

is needed to grade criteria and to determine importance levels. Decision-makers compare the criteria and sub-criteria in an evaluation form prepared using Saaty's scale of 1–9. The priorities of decision alternatives are listed by comparing all criteria [28].

In his work on decision-making with AHP, Saaty notes that decision-makers had preferences when considering the importance, possibility of realization, and their wishes for choosing situations or decision alternatives. He states that they chose the most suitable alternative with an estimated risk, cost, and benefit estimation using past experiences and observations [29]. AHP is said to be a reliable tool in determining the importance of criteria and sub-criteria sets and facilitating systematic and logical decision-making processes [30]. It is also a flexible and powerful tool for dealing with qualitative and quantitative multi-criteria problems [31]. The AHP method, which is applied by making a group decision, is more suitable than the Delphi technique [32]. As in many statistical studies, the quality of communication with the participants in the AHP method has an important effect on consistency and ranking of the results [33].

A review study on AHP, compiled from studies using the 150 AHP method, found that AHP plays a very important role in prioritizing and separating different goals and criteria in planning scenarios. In developing countries such as India and China, the use of the method is increasing. The authors say that software assistance will be preferred in scenarios that use hybrid methods [34].

Decisions to determine the best possible outcome by reducing the importance of AHP criteria and sub-criteria to a single dimension are determined by priority vectors that make up the ranking. AHP is an effective method used to reach a common judgment by expressing the opinions of people who are experts in a subject.

After the creation of the hierarchical structure for the decision problem, it is necessary to make binary comparisons of elements at the relevant level in order to calculate the priority values of the criteria at each level of the hierarchy. The following steps are followed to solve decision problems using the AHP technique [35]:

- Defining the decision-making problem, determining the purpose;
- Listing the decision criteria required to achieve the goal;
- Determining possible decision alternatives;
- Creating the hierarchical structure of the decision problem;
- The pairwise comparison of criteria for each level of the hierarchy and calculation of priorities;
- The pairwise comparison of alternatives according to the criteria and calculation of their priorities;
- Sorting the alternatives according to their relative priority values and selecting the alternative with the highest priority value.

The priorities of the criteria are obtained as a result of pairwise comparisons. Decision-makers do not have to make numerical comparisons, this can be done verbally [36]. In pairwise comparisons, the 1–9 scale of Saaty shown in Table 2 is generally used.

Table 2. Pairwise comparison scale.

Importance Level	Definition	Statement
1	equal importance	both options are equally important
3	moderately more important	one option is a little more important than the other
5	strongly more important	one option is much more important than the other
7	very strongly important	one option is far more important than the other
9	extremely important	one option is extremely important than the other
2, 4, 6, 8	intermediate values	when you fall between two levels

The general structure of the paired comparison matrix, which is the result of the binary comparison of the n criteria, with criteria $C_1, C_2, C_3, \dots, C_n$ and weights of $W_1, W_2, W_3, \dots, C_n$ according to their relative importance weights, is as follows [37]:

$$A = \begin{pmatrix} C_{11} & \cdots & C_{1n} \\ \vdots & \ddots & \vdots \\ C_{1n} & \cdots & C_{nn} \end{pmatrix} \quad (1)$$

The priority matrix is obtained from the matrix, obtained after the comparisons are made. The eigenvector or priority matrix consists of the weights of the criteria. In other words, it represents the local weights on which criterion is important. By multiplying the comparison matrix and the priorities matrix, the weighted total matrix is obtained in the structure below [36]:

$$W = \begin{bmatrix} \frac{w_1}{w_1} & \cdots & \frac{w_1}{w_n} \\ \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} \quad (2)$$

In the pairwise comparisons phase, the consistency ratio (CR) should be calculated to understand if the decision-makers responded to the questions consistently and reliably. In order to reach a consensus on how consistent the comparisons made through the questionnaires are, the inconsistency rate is calculated [36]. The consistency ratio can be calculated with the formula below.

$$CR = \frac{CI}{RI} \quad (3)$$

CR: consistency ratio

CI: consistency index

RI: random index

The consistency index (CI) can be calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

λ_{max} : the highest eigenvalue of the matrix

n : the order of pairwise comparison matrices

m : the number of independent rows of the matrix

In the case of $CR \leq 0.10$, it is accepted that the participant behaves consistently during the interview. In this case, the obtained weights can be used in the study. If $CR > 0.10$, it is understood that the decision-maker does not act consistently, and the participant is interviewed again and the comparisons are evaluated, thus, ensuring consistency. If the consistency of the revised matrices is still unattainable, these matrices are not included in the analysis.

The main reasons why the AHP method is easier to apply than other multi-criteria decision-making methods are as follows [38]:

- It is naturally evaluated, and the method is easy to apply;
- There is no need for an advanced level of expertise to apply;
- It is based on people's quantitative values and experiences.

The rules required to ensure a healthy result from the AHP method are as follow [39]:

- The problem and target that will be the subject of the application should be determined exactly;
- The most appropriate criteria, sub-criteria, and decision alternatives should be chosen;
- The differences between decision alternatives should not be too much;
- Decision alternatives must be independent of each other.

3. Application

The most appropriate selection of natural rubber and compounds used in rubber production in terms of sustainability were made using the AHP method. The study was carried out in three stages for the main natural rubber raw material, filler, and oil. In determining the decision problems and all subsequent decisions, evaluations were made with a decision-making group specifically assembled for the project. The decision-making group consisted of members of the International Sustainability and Energy Research Association (SARES), academics in related fields, and engineers working in the car tire manufacturing sector. As such, the study's aims were transformed into a decision problem, in accordance with the method, to be used for all these stages. Decision problems related to these stages were formed as follows:

- The environmentally friendly natural rubber selection problem;
- The environmentally friendly filler selection problem;
- The environmentally friendly process oil selection problem.

After defining the problems, the criteria and alternatives that would constitute the decision-making structure for each stage were determined. After determining all the elements, the decision problem was transformed into a hierarchical structure in accordance with the method.

3.1. Natural Rubber Selection Structure

In the first stage of the study, *Hevea brasiliensis* (Hevea rubber), which is the most widely used natural rubber in the production of car tires in the world, and its possible natural alternatives were evaluated. All three rubbers considered as alternatives are natural rubber products based on polyisoprene, only of different biological origin. The criteria and alternatives in the rubber selection problem were determined and a structure was created as shown in Figure 1.

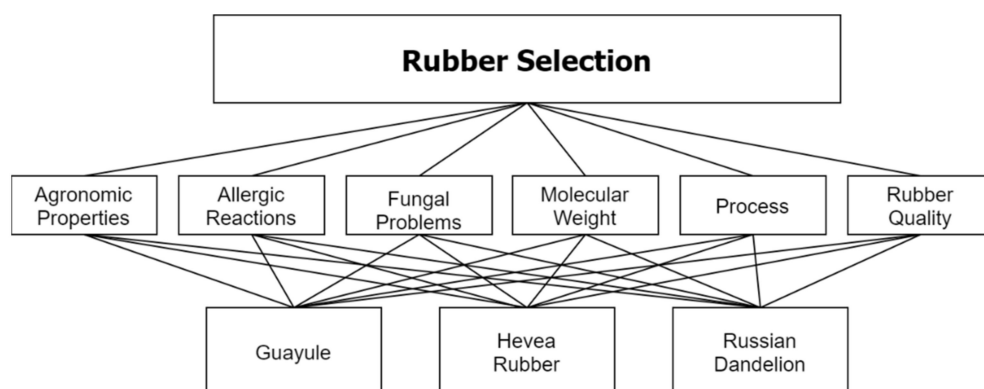


Figure 1. Hierarchical structure of natural rubber selection.

Hevea rubber (*Hevea brasiliensis*) is the most important natural rubber that has been used the most by humans for several centuries. Hevea is mainly a hydrocarbon with over 2000 varieties and is obtained from the plant *Hevea brasiliensis* [40]. Almost half of the rubber consumed today is obtained from Hevea [4].

The second alternative, Guayule (*Parthenium argentatum*), is one of the natural rubbers which, according to recent studies, is estimated to be used second to Hevea in the future [40]. Guayule is a perennial woody plant native to the South American region.

The last alternative, the Russian Dandelion (*Taraxacum kok-saghyz*), is a species of dandelion originating from Kazakhstan. It was discovered by the USSR as part of strategic research conducted for the indigenization of natural rubber [7].

After the alternatives were identified, criteria were determined to make comparisons between them. The criteria were chosen to cover all processes, from seed sowing to the final use of the rubbers, and were as follows:

- Agronomic properties: all factors affecting the cultivation of the rubber plant;
- Allergic reactions: the damage of rubber to human health;
- Fungal problems: the susceptibility of the rubber plant to agricultural diseases, especially fungi;
- Molecular weight: considering the structure of natural rubber, it is desired that natural rubber has a high molecular weight. The tensile strength is higher for polymers with a higher molecular weight;
- Process: the natural rubber process should start with latex harvesting from rubber trees and be as fast, cheap, and sustainable as possible until it is brought into the desired form;
- Rubber quality: natural rubber should meet the desired properties at the highest possible level.

3.2. Environmentally Friendly Filler Selection Structure

Fillers are added to the rubber mixture for various purposes such as reinforcement, cost reduction, and support. Thus, the rubber products obtained have features such as longer life, higher strength, and more satisfactory flexibility. In the production of tires, 30–35% by mass of filler additive is used. With this ratio, fillers are the second most used material in rubber by mass [41]. Currently, carbon black, which has a significant carbon footprint, is used in tire production. The hierarchical structure was created for the filler selection problem as shown in Figure 2.

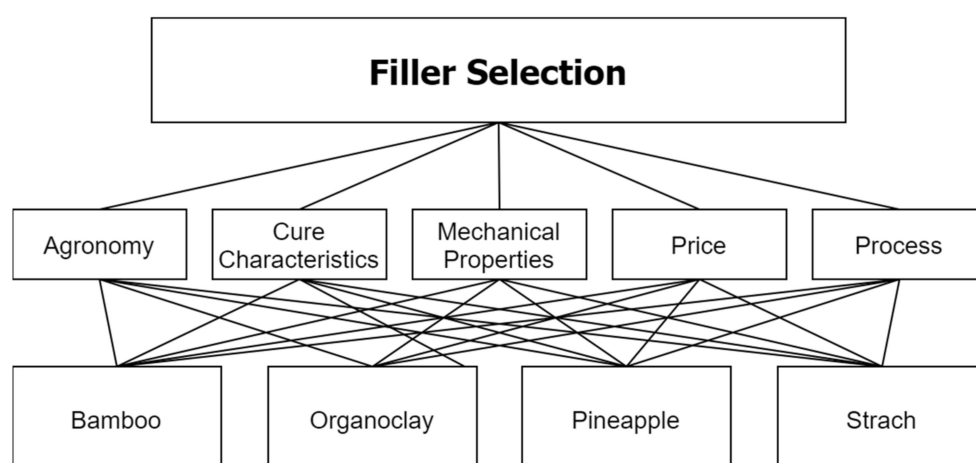


Figure 2. Hierarchical structure of filler selection.

Environmentally friendly alternatives, which are the subject of the most-cited studies in academic literature in recent years, were identified and included in the study as alternatives. At this stage, fillers from bamboo, organoclay, pineapple, and starch, which are environmentally friendly alternatives to carbon black, were evaluated. In this evaluation, the criteria presented and briefly explained in the hierarchical structure below were used.

- Agronomy: it is expected that the filler plant will provide convenience in terms of agricultural cultivation and collection;
- Cure characteristics: in terms of curing properties, it is expected that the additive will be as fast and efficient as possible;
- Mechanical properties: it is expected that the additive material used will improve the mechanical properties of the product to be produced;
- Price: it is desirable to obtain the additive material as cheaply as possible;
- Process: processes in the raw material to product conversion stages are required to be cost-effective, short-term, and simple.

3.3. Environmentally Friendly Oil Selection Structure

Oils or softeners are used as process facilitators in the preparation of the mixture. Process facilitation can occur at different stages of production, for example: reducing friction during mixing by wetting rubbers and fillers, ensuring that the mixture is homogeneous, increasing the fluidity of the mixture, and making the mixture easier to process. Mineral oils (paraffinic, naphthenic, aromatic) are generally used in tire production. The ratio of these oils in the rubber mixture is 15% together with resin [42]. Therefore, the use of environmentally friendly oil alternatives would make a significant contribution to sustainability. At this stage, by looking at the citations of the relevant studies, cardanol, palm, soybean, and sunflower oils, which have been studied more in the current literature, were determined as the most important alternatives. The criteria and alternatives in the oil selection problem were determined and a structure was created as shown in Figure 3.

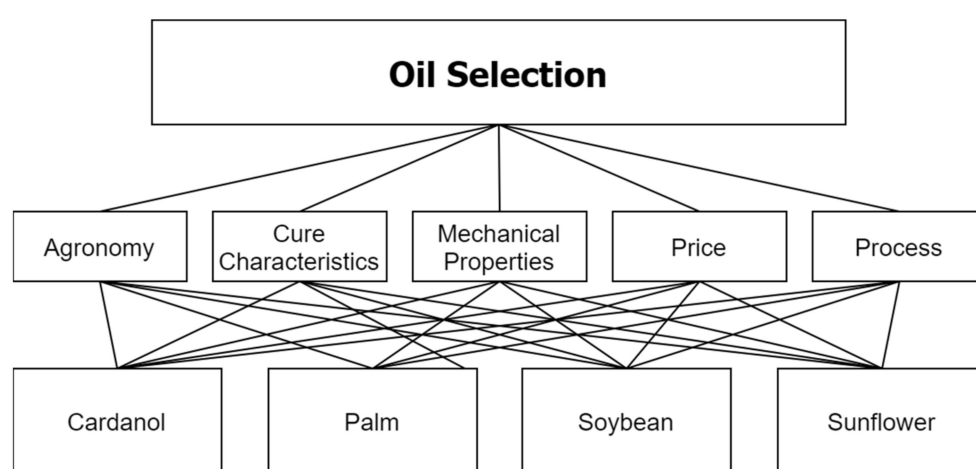


Figure 3. Hierarchical structure of oil selection.

The criteria used in the hierarchical structure here are the same as those used in the filler selection problem. Similar criteria were considered appropriate in both decision problems as both used materials obtained from natural sources instead of synthetic options.

The criteria to be used in every selection stage were determined to cover all processes from seed to production and from raw material to final product. In order to cover all processes, the areas where the alternatives differ were included in the criteria. While determining the differing points, we aimed to ensure the alternatives could be evaluated sufficiently. Moreover, although the criteria for filler and oil are the same in name, decision-makers took into account the specific factors that these criteria would affect in the context of each relevant alternative.

4. Results

After determining the alternatives and criteria, hierarchical structures of decision problems were formed by determining their relations with each other. With the determination of hierarchical structures, pairwise comparisons were ready for decision-making. Pairwise comparisons were made by the decision-making group using the group decision-making method. The consistency ratio remained below 0.1 for all paired comparisons. Thus, it was confirmed that all evaluations were made properly. Both the most suitable alternatives and the weights of the criteria were determined from the resulting matrices.

4.1. Environmentally Friendly Natural Rubber Selection Results

In the first part of the results, the weights in natural rubber selection were determined. The weights of the criteria used in this decision problem are given in Figure 4. As it can be understood from this figure, molecular weight emerges as the criterion that has the greatest impact on the decision, with a value of 0.43. Criteria can be listed as rubber quality,

process, agronomic properties, fungal problems, and allergic reactions, according to their effect on the decision. Among the criteria, the values of 0.07, 0.04, and 0.03 and agronomic properties, fungal problems, and allergic reactions, respectively, had a very low effect on decision making. Allergic reactions were the least effective criterion, as the end product is a car tire. If the final product was a product used by humans in contact, this criterion would have a higher weight.

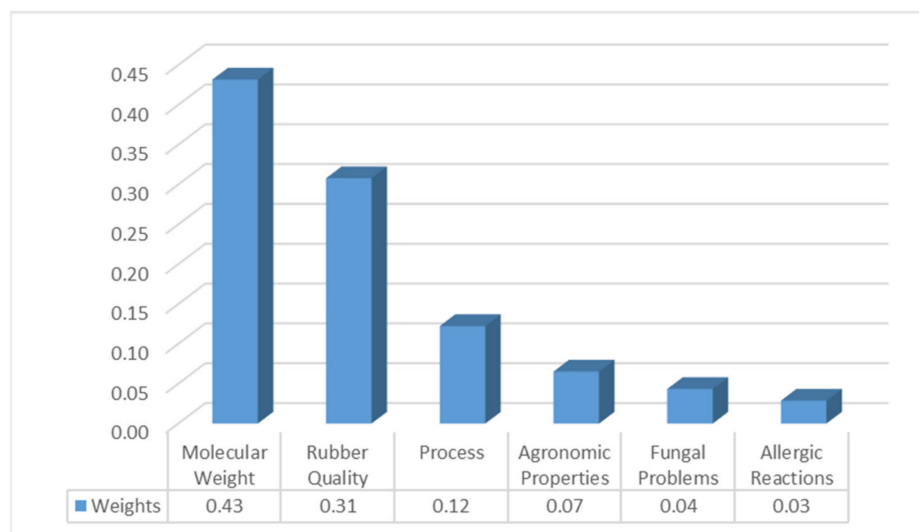


Figure 4. Weights of the rubber selection criteria.

The weights of the alternatives for the decision problem are shown in Figure 5. When we look at the values here, Russian Dandelion is the most suitable alternative, with a value of 0.58, and Guayule is the weakest alternative, with a weight of 0.16. Considering these values, it can be inferred that the use of the Russian dandelion plant in the production of rubber used in car tire production would be the most sustainable.

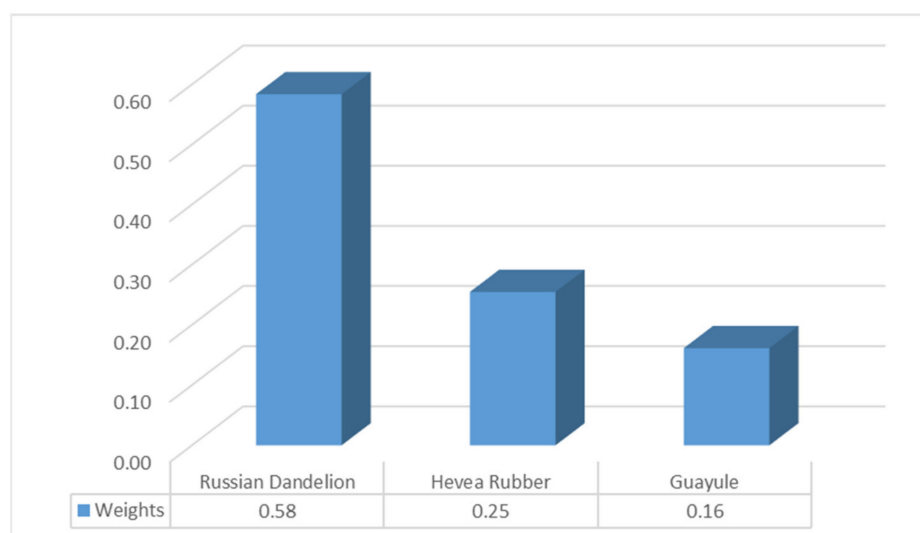


Figure 5. Weights of the rubber alternatives.

4.2. Environmentally Friendly Filler Selection Results

The second decision problem of the study was examined to determine which filler would be the most appropriate and sustainable. First, the weights of the criteria that affect the decision were determined, these values are presented in Figure 6. When these values were examined, it was seen that the most important criterion in the selection of

fillers to be used in the mixture was a filler's mechanical properties, with a weight of 0.49. Other important criteria were agronomy and price criteria, with values of 0.24 and 0.14, respectively. Process and cure characteristics criteria were calculated as the least influencing criteria with values of 0.08 and 0.04, respectively. Since the material will be used in car tires, it is understandable that the mechanical properties criterion has the highest weight.

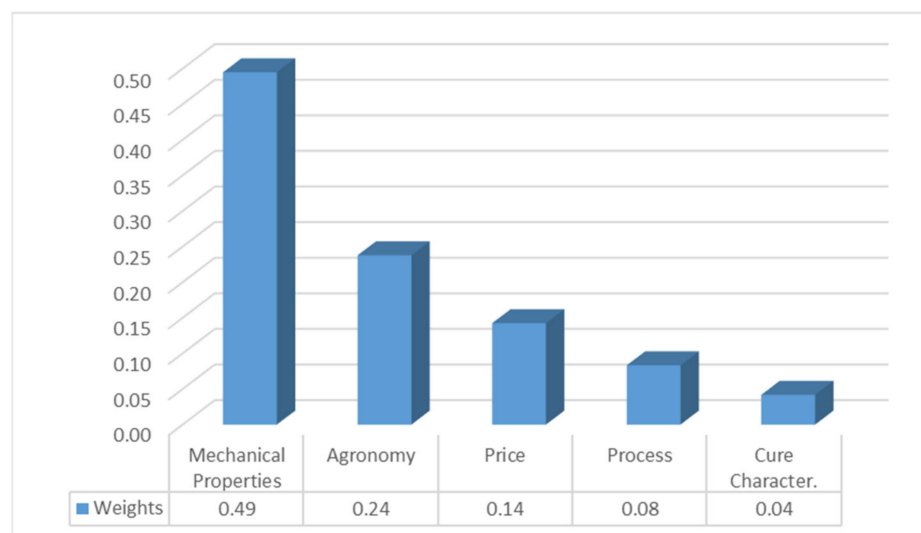


Figure 6. Weights of the filler selection criteria.

The weights of the alternatives were determined by using the weights of the criteria and the results are shown in Figure 7. Looking at the results, bamboo was seen to be the best alternative, with a value of 0.41, and organoclay to be the least suitable alternative, with a value of 0.11. Pineapple and starch were intermediate alternatives, with values of 0.30 and 0.18, respectively. These results suggest that car tires would be more sustainable by using bamboo instead of carbon black as fillers in tire production.

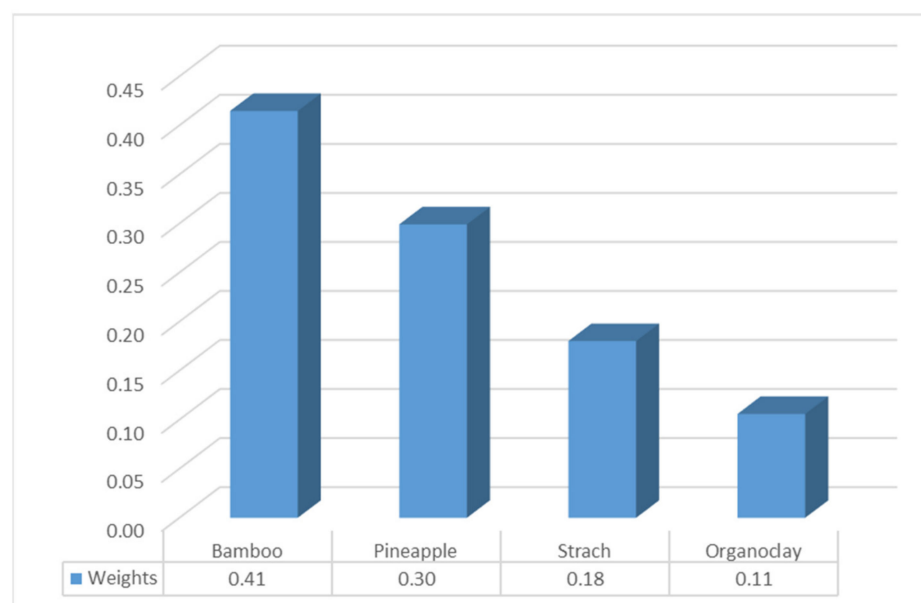


Figure 7. Weights of the filler alternatives.

4.3. Environmentally Friendly Oil Selection Results

In the final decision problem, oils used in the softening stage in tire production were evaluated. The criteria in the previous decision problem were used here in the evaluation

of oil alternatives and their values are given in Figure 8. Here again, mechanical properties were the most important criterion, with a value of 0.49. The other criteria had the same ranking as the fillers problem with the same values. The reason for this is likely to be due to the fact that the alternatives in both decision problems are all of natural origin and their intended use is the same.

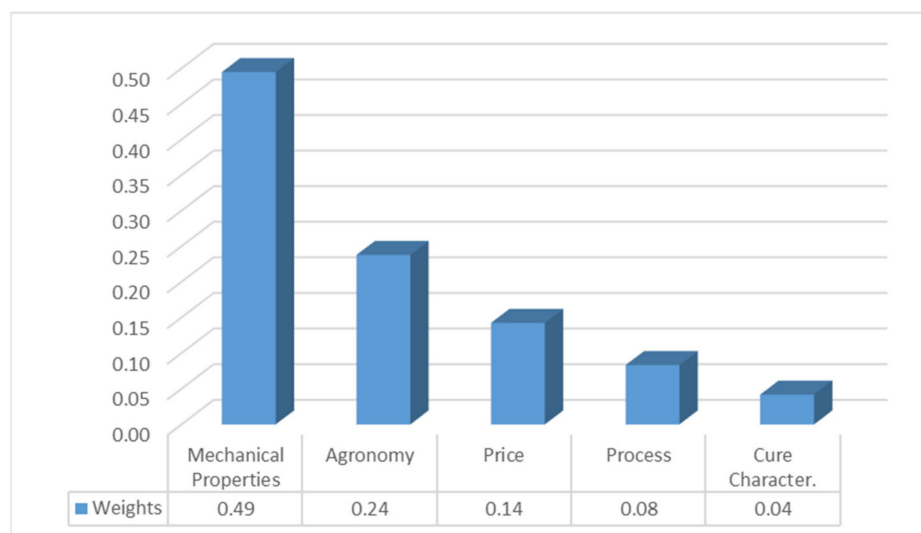


Figure 8. Weights of the oil selection criteria.

Values of the alternatives for the final decision problem of the study are given in Figure 9. Palm oil emerged as the best alternative, with a value of 0.41. It was followed by sunflower and soybean, with values of 0.29 and 0.19, respectively. Cardanol was the least suitable alternative, with a value of 0.11. These results reflect the good mechanical properties of palm oil and the fact that it is widely used at present.

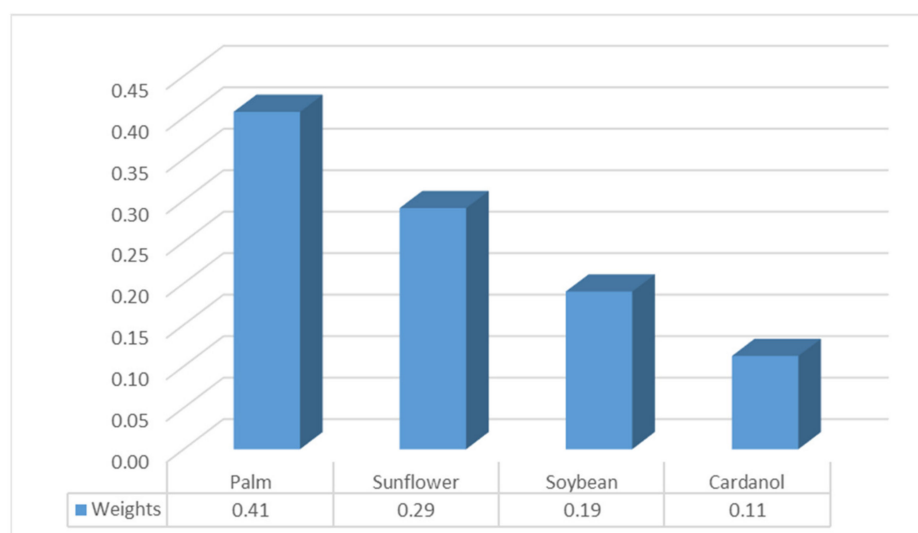


Figure 9. Weights of the oil alternatives.

5. Discussion

This study presents a sustainability evaluation of rubber, filler, and oil alternatives presented in recent literature for use in tire production. Previous studies included the determination and comparison of the chemical and physical properties of materials. In this study, contributing to this knowledge, a comparison of the most suitable alternatives for a particular product using a scientific method was made.

The study was carried out in three stages, more sustainable alternatives for approximately 90% of the materials used in tire production by mass were investigated. Russian dandelion was found to be the most suitable rubber, bamboo as the most suitable filler, and palm oil as the most suitable oil. Although Hevea is currently the most used natural resource among the rubber alternatives evaluated, it was still included. As such, the question of whether there is a more sustainable option for the current situation was asked. Russian dandelion was found to be the best sustainable alternative. Bamboo was found to be the most appropriate as a partial substitute for carbon black and silica in tire compounds due to its mechanical properties. In addition, it may be an excellent sustainable option in areas other than the tire industry that require less load and strength. In other decision problems from previous studies, the materials currently used were synthetic, non-green, high emission, and unsustainable products. All of the alternatives that are deemed suitable by this study are of natural origin.

In this study, alternatives to rubber and its compounds used in car tires were investigated. However, the use of rubber is not limited to this application. Therefore, different criterion weights and different alternative weights may be found in studies that examine alternatives to rubber and compounds used for different purposes.

We believe that the method used in this study could be used in future studies in different areas of the rubber industry and in sustainability studies in other sectors. Importantly, in this study, guides were presented to decide which points should be considered in future rubber and additive studies.

The choices made in this study were made only within the framework of sustainability, and the physical properties of the target product were not assessed. The evaluations made in terms of sustainability in this study may guide future studies by blending them with the assessment of physical properties.

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